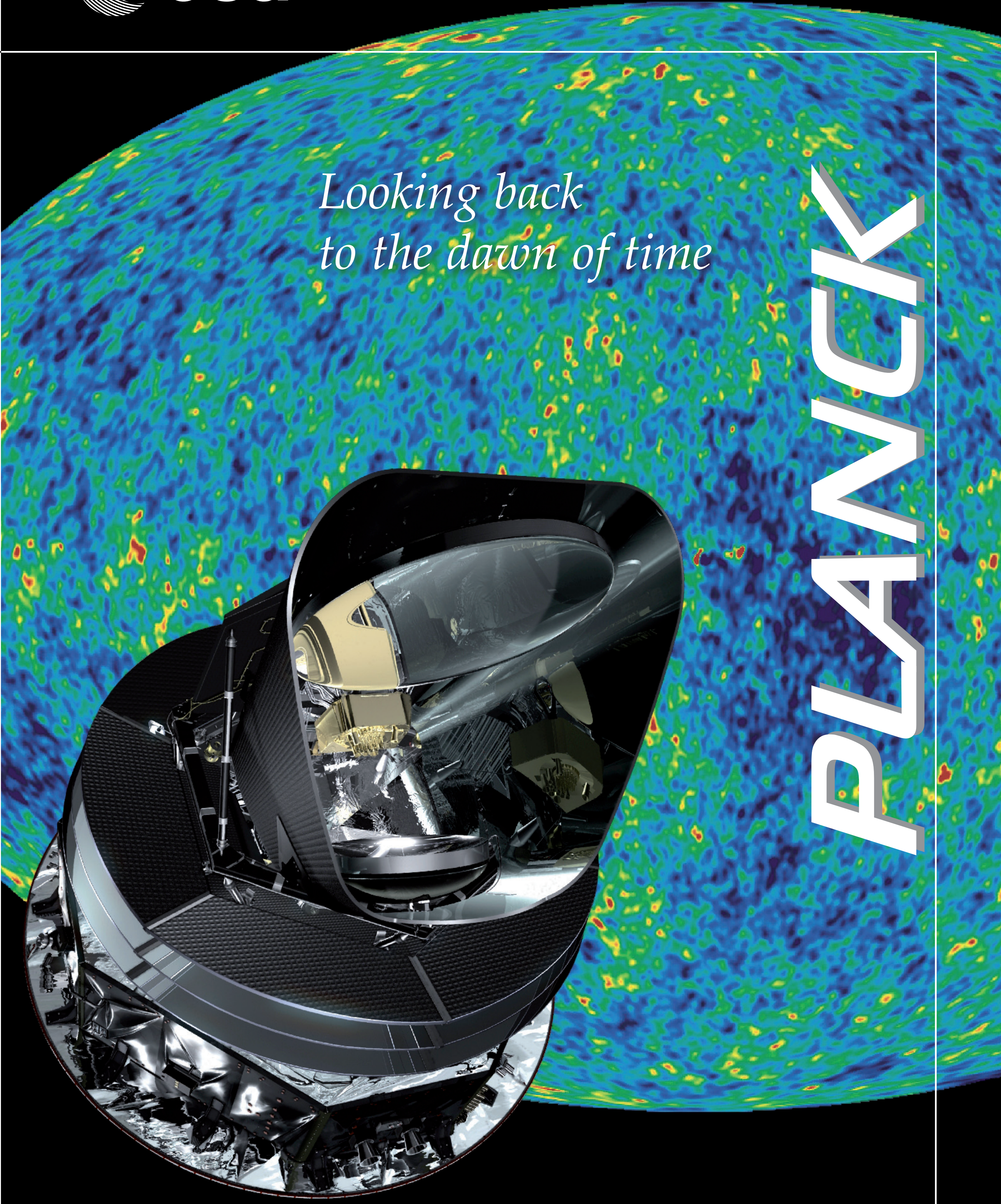
BR-275

PLANCK

Looking back to the dawn of time



European Space Agency
Agence spatiale européenne

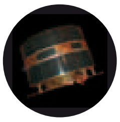
About ESA

The European Space Agency (ESA) was formed on 31 May 1975. It has 18 Member States: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

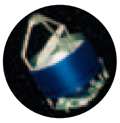
The ESA Science Programme has launched a series of innovative and successful missions. Highlights of the programme include:

Cassini-Huygens is one of the most ambitious planetary exploration efforts ever attempted. After a seven-year journey, the Cassini orbiter began studying the Saturnian system in great detail, and the Huygens probe descended onto Saturn's giant moon Titan, unveiling an amazing cold but Earth-like world.

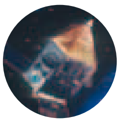
Cluster, which is a four-spacecraft mission to investigate in unprecedented detail the interaction between the Sun and the Earth's magnetosphere.



Double Star, following in the footsteps of the Cluster mission, with its two spacecraft it studies the effects of the Sun on the Earth's environment.



Giotto, which took the first close-up pictures of a comet nucleus (Halley) and completed flybys of Comets Halley and Grigg-Skjellerup.



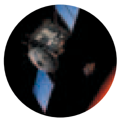
Hipparcos, which fixed the positions of the stars far more accurately than ever before and changed astronomers' ideas about the scale of the Universe.

Hubble Space Telescope, a collaboration with NASA on the world's most important and successful orbital observatory.

Integral, which is the first space observatory that can simultaneously observe celestial objects in gamma rays, X-rays and visible light.

Infrared Space Observatory (ISO), which studied cool gas clouds and planetary atmospheres. Everywhere it looked, it found water in surprising abundance.

International Ultraviolet Explorer (IUE), the first space observatory ever launched, marked the real beginning of ultraviolet astronomy.



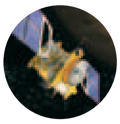
Mars Express, Europe's first mission to Mars, which is providing an unprecedented global picture of the Red Planets' atmosphere, surface and subsurface.

Rosetta, Europe's comet chaser, will be the first mission to fly alongside and land on a comet, probing the building blocks of the Solar System in unprecedented detail.

SMART-1, Europe's first mission to the Moon, which tested solar-electric propulsion in flight, a key technology for future deep-space missions.

Solar and Heliospheric Observatory (SOHO), which is providing new views of the Sun's atmosphere and interior, revealing solar tornadoes and the probable cause of the supersonic solar wind.

Ulysses, the first spacecraft to fly over the Sun's poles.



Venus Express, which is probing the mysteries of Venus's atmosphere with a precision never achieved before

XMM-Newton, with its powerful mirrors, is helping to solve many cosmic mysteries of the violent X-ray Universe, from enigmatic black holes to the formation of galaxies.

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More information can also be obtained via the ESA Science website at: **www.esa.int/planck**

An ESA Communications Production

Publication	Planck – Looking back to the dawn of time (ESA BR-275 February 2009)
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Publisher	ESA Communication Production Office ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands Tel: +31 71 565 3408 Fax: +31 71 565 5433 www.esa.int
Printed in	The Netherlands
Price	€7
ISBN	978-92-9221-014-4
ISSN	0250-1589
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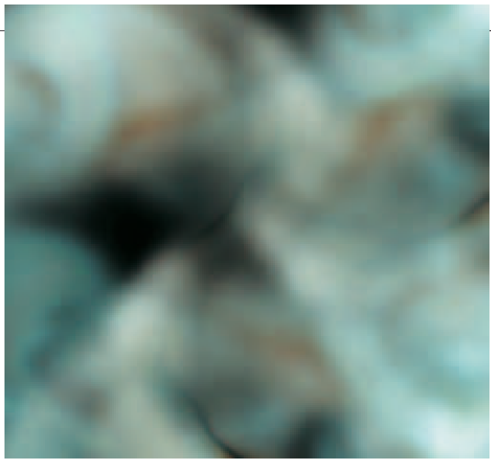
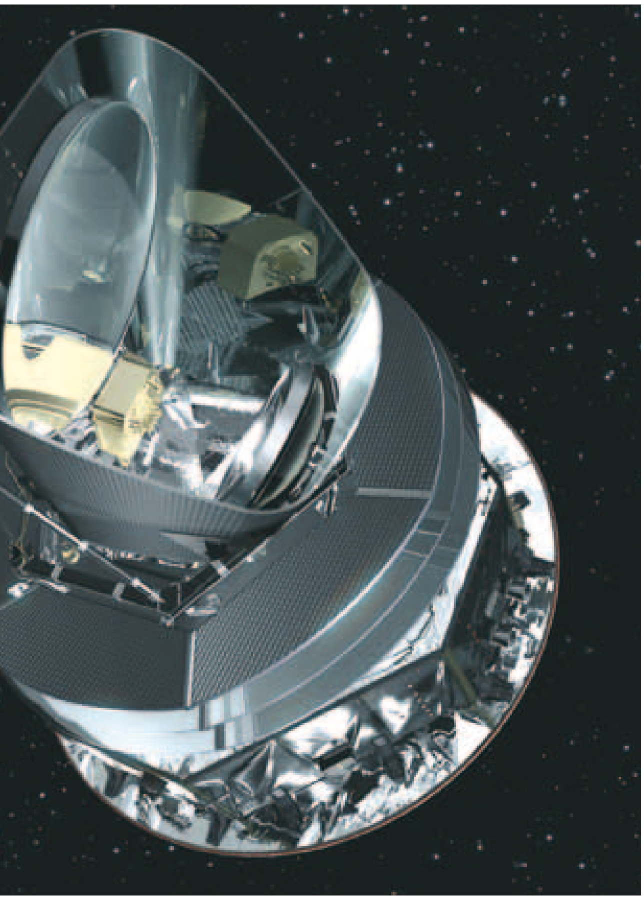
Understanding the origin and evolution of our Universe



The early days of the Universe are shrouded in mystery.

Only a century ago, the origin of the Universe was a topic that few scientists dared to touch: they simply lacked the experimental means to gather reliable data. The situation is quite different now. Cosmology, the science that aims to explain how the Universe formed and evolves, has become one of the richest and hottest fields of experimental research.

Key discoveries made during the last eight decades indicate that in the past the Universe was far denser and hotter than it is today, and that it started to cool and expand – a process that is still going on today – about 13 700 million years ago. This version of events, known as the Big Bang theory, is widely accepted. But the picture is still far from complete. Questions such as what triggered the birth of the Universe, or how it will evolve in the future, remain unanswered.



ESA's Planck microwave observatory. ESA (AOES Medialab)

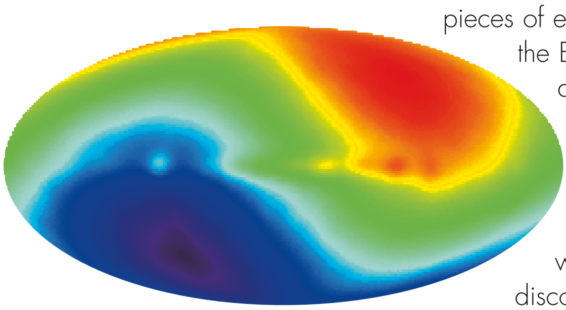
These questions, though, are no longer untouchable. Contrary to the situation a century ago, scientists now know where to look for the answers, and they are steadily gaining the means to do so. The era of experimental cosmology is indeed in full swing: ongoing experiments on ground and in space are yielding new and exciting results. And in the coming years the field will be enriched with more complex space-based instruments that are specifically designed to tackle fundamental problems.

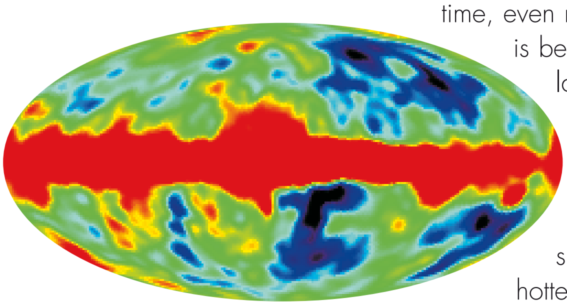
The Planck observatory, an ESA mission due to be launched in 2009, is the most ambitious of these space-based missions. Planck will provide the most precise and reliable data of its kind ever obtained, and by doing so it will take scientists the closest ever to the origin of our Universe. Planck has been built by European industry and scientific institutes all around Europe and the USA to help solve many of the big questions still pending in cosmology.

Detectives of the past and the future

An expanding Universe with a hot past

Scientists trying to reconstruct an event that took place about 13 700 million years ago work very much like detectives. First they have to find the right clues, then they have to squeeze all the useful information out of those pieces of evidence. The case of the Big Bang is a long and difficult one. It started in the 1920s, when astronomers learnt that the Universe has not always been as we see it today. They discovered that all the time, even right now, the Universe is becoming larger and larger. This means that in the past all the matter and energy that it contains were packed into a much smaller, and also much hotter, region.





Maps of the sky as seen by NASA's COBE satellite, after different stages of image processing. The top panel shows (in false colour) the temperature of the sky after removing a uniform (2.7 K) component due to the CMB; the large-scale diagonal feature (the so-called dipole) is caused by the motion of the Sun with respect to the CMB; and the faint horizontal smudge is due to emission from the Milky Way. The bottom map results when the dipole component is removed. What is left is residual galactic emission (seen as a bright horizontal band), and a background of hot and cold spots, due largely to a mixture of instrument noise and the CMB.

Later on a second clue was identified. Scientists learnt that the stars are the 'factories' that make most chemical elements in the Universe – oxygen, carbon, iron – but also that some particular elements must come from somewhere else. They postulated, and confirmed, that those few elements had been produced during the earliest epochs of the Universe, when it was still very hot.

The first light

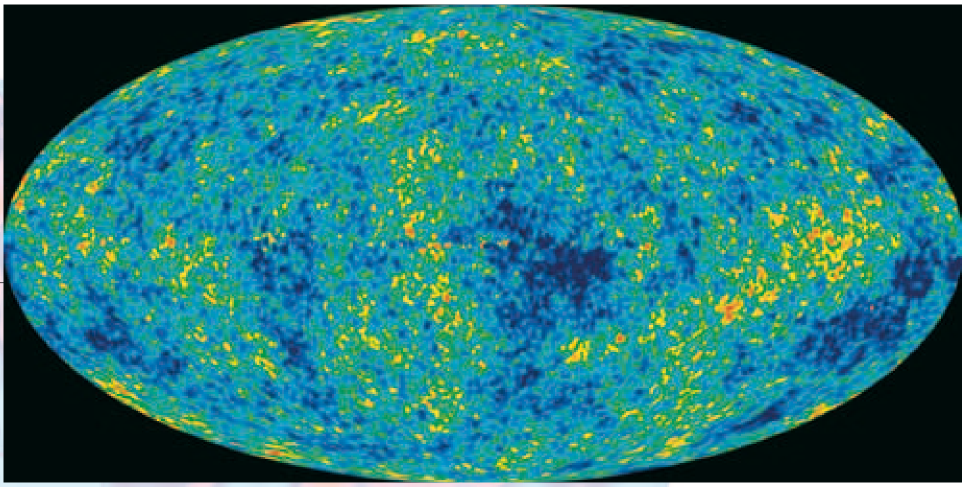
Those findings helped to give shape to the Big Bang theory. But this general model describing the beginning of the Universe did not gain wide support from the scientific community until the discovery of yet a third clue. In 1964, two researchers serendipitously detected radiation coming from everywhere in the sky, a 'glow' filling the whole Universe with the same intensity. This radiation could best be interpreted as a 'fossil' of the Big Bang itself.

The argument goes like this: if the Universe has always been expanding, then there must have been an initial period during which all existing matter and radiation were very tightly coupled together, in a high-temperature mixture. With time the Universe cooled down, and at some point it must have reached a temperature low enough for the radiation to be released from its close embrace with matter. Light would then have travelled freely throughout the Universe for the first time. That 'first light' should still be detectable today, and it was, in fact, the glow detected in 1964.

Scientists call this first light Cosmic Microwave Background (CMB) radiation. It is important not only because it is the third major piece of evidence supporting the Big Bang theory, but also because cosmologists know that they have not yet been able to extract all the information it holds. They still need to work hard on the fossil radiation.

'Clots' of information

The CMB comes from every direction in the sky with almost the same brightness. But by measuring its apparent temperature all over the sky, scientists discovered that tiny differences do exist from place to place. These differences can be as small as one part in a million.



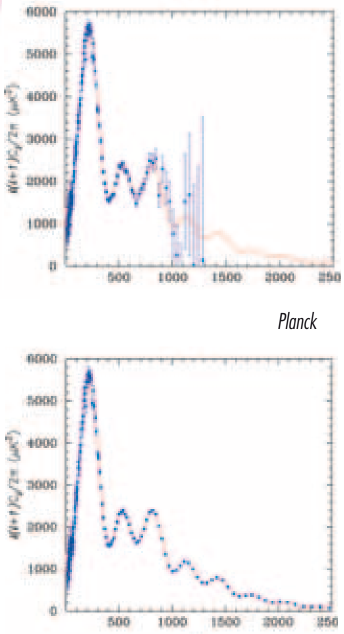
In 1992, NASA's COBE satellite confirmed for the first time that the temperature of the Cosmic Microwave Background (CMB) was not uniform over the sky. The COBE measurements indicated that over angular scales larger than 10°, the temperature of the CMB varies by about one part in 100 000 from the average value of 2.73K. In 2003, COBE's successor WMAP was able to improve dramatically the map's clarity and sharpness; the image shows the tiny irregularities in the temperature of the CMB across the sky, as mapped by WMAP. (NASA)

Although these variations may seem too small to be important, they are precisely what scientists are looking for. They contain a goldmine of information. They are nothing less than the imprints left in the past by matter, a reminder of the period when matter and radiation were closely coupled to each other. At that time matter already contained the 'seeds' of the huge structures that we see in the Universe today: galaxies and galaxy clusters. The tiny variations in the measured temperature of the CMB are the imprints left by those clots of matter.

In fact, much of the valuable information that the CMB can provide lies in the precise shape and intensity of these temperature variations, called anisotropies. In 1992, NASA's COBE satellite obtained the first blurry signals of the anisotropies of the CMB. In 2003, its successor, NASA's WMAP was able to chart maps that have started to reveal their detailed properties. The objective of Planck is to complete the picture by mapping these features as fully and accurately as possible.

WMAP

Planck



Simulations of observations of the CMB show the dramatic improvement that can be achieved by increasing the angular resolution and sensitivity of an experiment from the level of WMAP (top panel) to the level of Planck (bottom panel). The quantity shown on these plots (called the angular power spectrum) encodes the amount of cosmologically relevant information available in the maps, reflected in the bumps and wiggles of the red curve. The blue bars show that Planck will be able to recover about 15 times as much relevant information as WMAP.

Some pending questions that Planck will help to answer

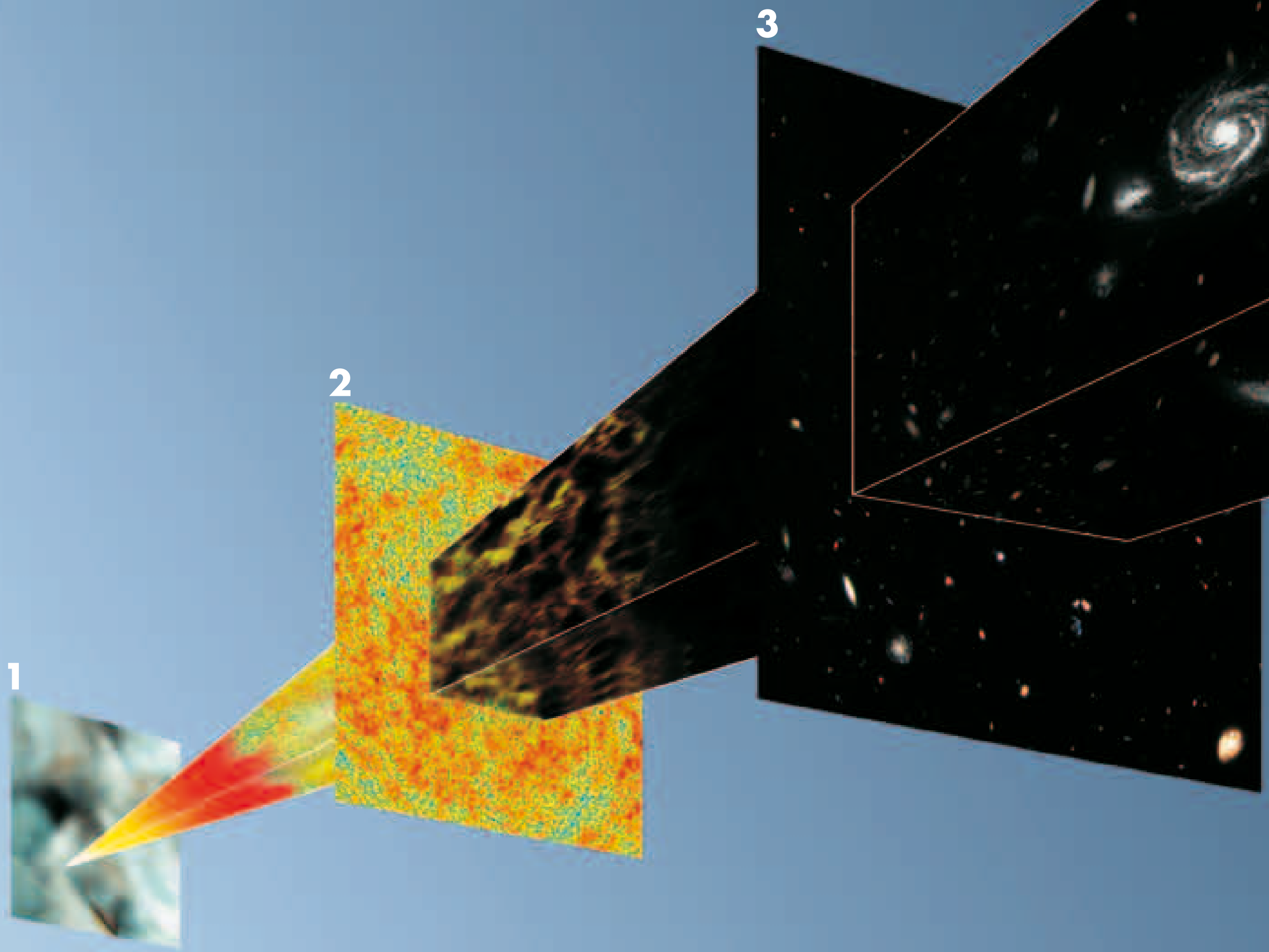
The anisotropies in the CMB hold answers to many key questions in cosmology. Some refer to the past of the Universe, such as what triggered the Big Bang and how long ago it happened. But some other questions look far into the future. For instance: what is the density of matter in the Universe and what is the true nature of this matter? These parameters will tell us if the Universe will continue its expansion forever or if, on the contrary, it will end up collapsing on itself in a process inverse to the Big Bang, called the 'Big Crunch'. Now, thanks to WMAP, we know that our Universe will most likely not crunch; but new insights are telling us that the fate of the Universe is less predictable than we thought.

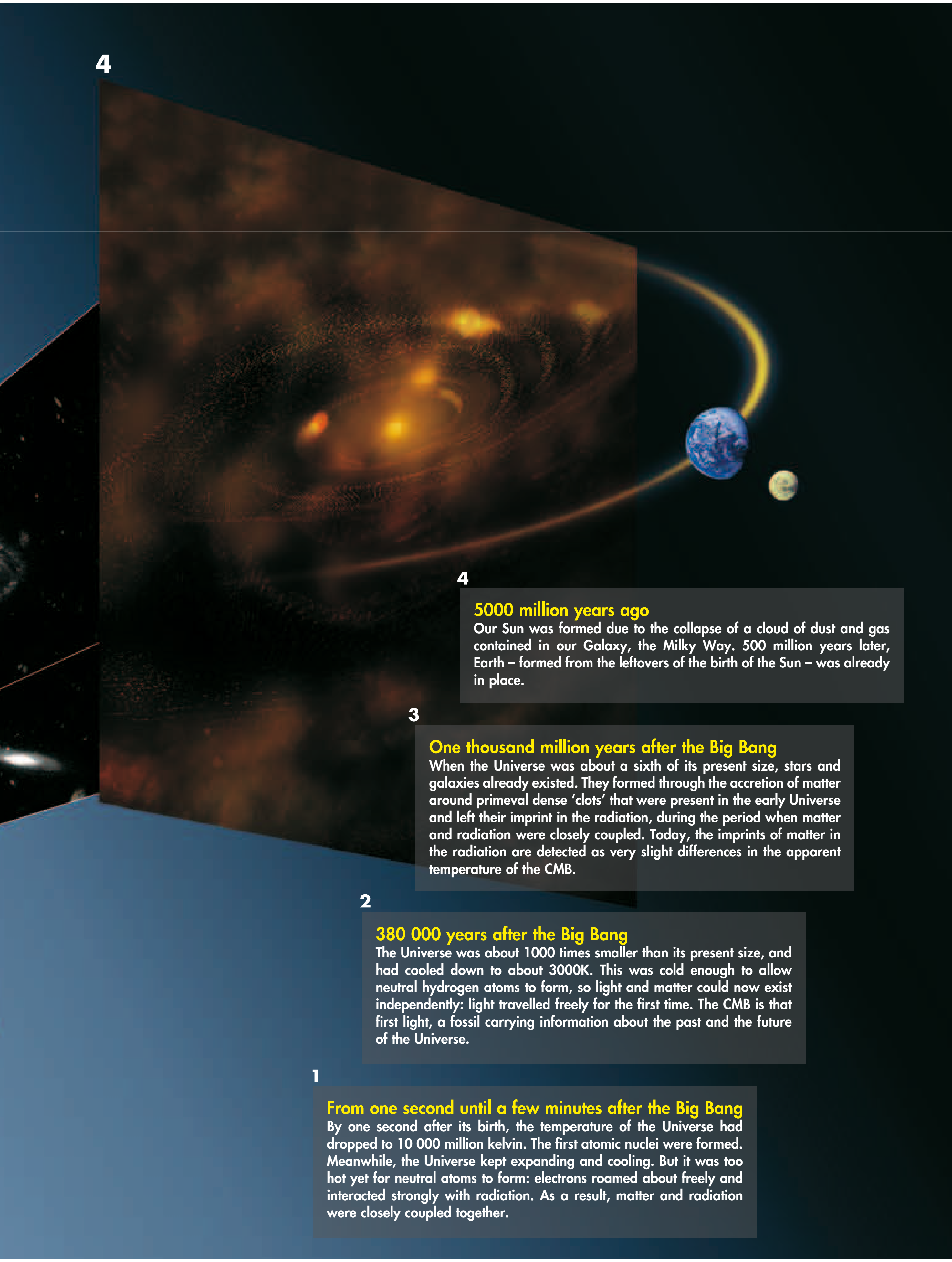
Some of the new uncertainties are related to the hypothesised existence of 'dark energy' which may exist in large quantities in our Universe, as indicated by recent observations measuring light from distant exploding stars. Is it really there? And if so, what are its effects? ESA's Planck satellite will help to unravel these mysteries.

A trip towards the origin of space and time

The birth of the Universe

The period up to a millionth of a second after the birth of the Universe is full of uncertainties: there are no concrete observations or speculation-free arguments to confirm or disprove theories regarding this period. According to the most accepted hypothesis, a very brief 'inflation process' took place at the beginning of this epoch. During this inflation process the Universe expanded extremely quickly by a huge factor, after which it expanded and cooled much more slowly. If this hypothesis is correct, then the inhomogeneities in the Cosmic Microwave Background will reflect some of the details of the event, and Planck will be able to provide us with the most reliable information about it.





4

5000 million years ago

Our Sun was formed due to the collapse of a cloud of dust and gas contained in our Galaxy, the Milky Way. 500 million years later, Earth – formed from the leftovers of the birth of the Sun – was already in place.

3

One thousand million years after the Big Bang

When the Universe was about a sixth of its present size, stars and galaxies already existed. They formed through the accretion of matter around primeval dense 'clots' that were present in the early Universe and left their imprint in the radiation, during the period when matter and radiation were closely coupled. Today, the imprints of matter in the radiation are detected as very slight differences in the apparent temperature of the CMB.

2

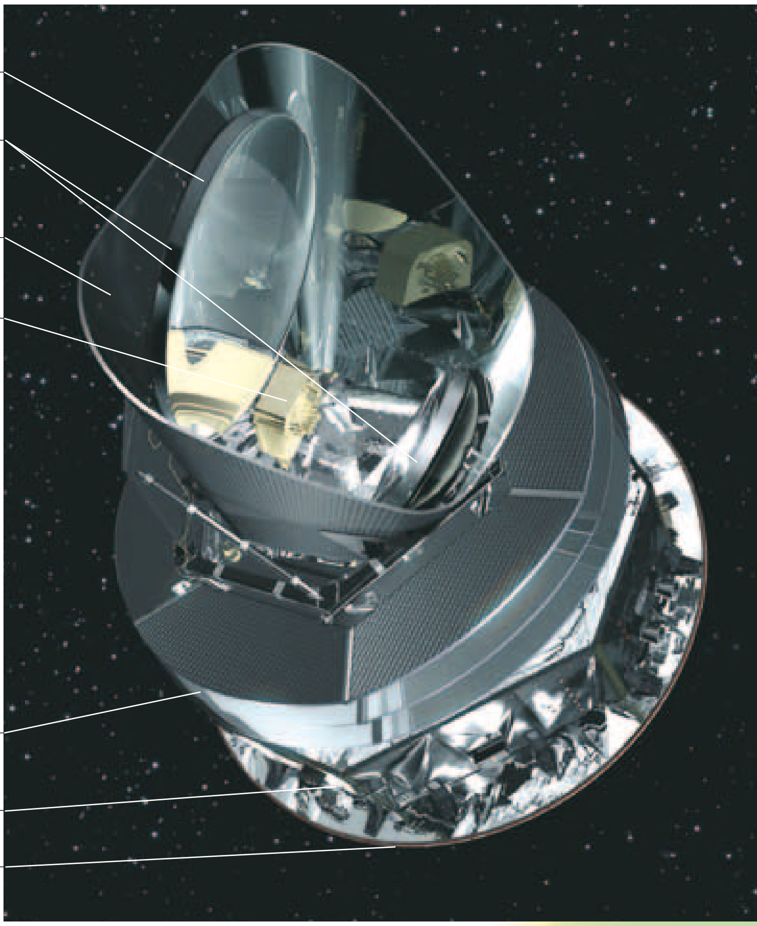
380 000 years after the Big Bang

The Universe was about 1000 times smaller than its present size, and had cooled down to about 3000K. This was cold enough to allow neutral hydrogen atoms to form, so light and matter could now exist independently: light travelled freely for the first time. The CMB is that first light, a fossil carrying information about the past and the future of the Universe.

1

From one second until a few minutes after the Big Bang

By one second after its birth, the temperature of the Universe had dropped to 10 000 million kelvin. The first atomic nuclei were formed. Meanwhile, the Universe kept expanding and cooling. But it was too hot yet for neutral atoms to form: electrons roamed about freely and interacted strongly with radiation. As a result, matter and radiation were closely coupled together.



ESA (AOES Medialab)

How will Planck work?

Sensing the temperature of the Universe

Planck will study the Cosmic Microwave Background by measuring its temperature all over the sky. Planck's large telescope will collect light from the CMB and focus it onto two arrays of radio detectors, which will translate the signal into a temperature reading.

The detectors on board Planck are highly sensitive. They will be looking for variations in the temperature of the CMB of about a million times smaller than one degree – this is comparable to measuring from Earth the heat produced by a rabbit on the Moon.

The Planck spacecraft

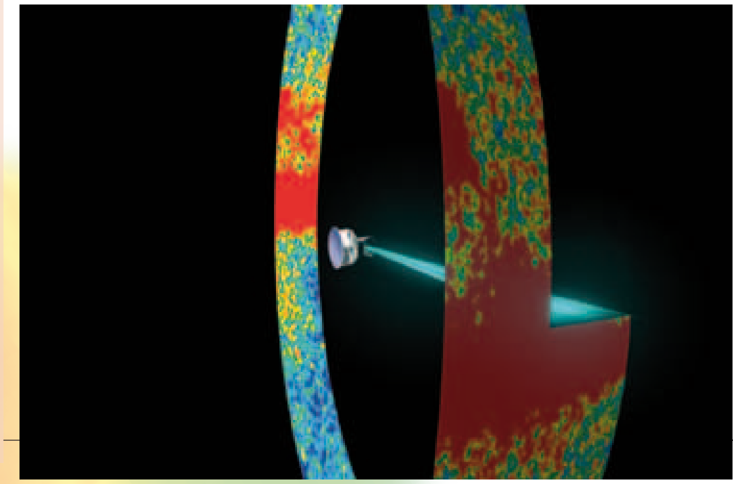
The Planck spacecraft consists of two main elements: a warm satellite bus, or service module, and a cold payload module which includes the two scientific instruments and the telescope.

The service module is octagonal. It houses the data handling systems and subsystems essential for the spacecraft to function and to communicate with Earth, and the electronic and computer systems of the instruments. At the base of the service module is a flat, circular solar panel that generates power for the spacecraft and protects it from direct solar radiation.

The baffle is an important part of the payload module. It surrounds the telescope, limiting the amount of stray light incident on the reflectors. It also helps radiate excess heat into space, cooling the focal plane units of the instruments and the telescope to a stable temperature of about −223°C (or 50K). The baffle forms part of the passive cooling system for the satellite, before the active cooling system takes over.

The solar array, located at the bottom of the service module at one end of the spacecraft, is permanently illuminated. Three reflective thermal shields isolate the service module from the payload module at the other end. This prevents the heat generated by the solar array and the electronic boxes inside the service module from diffusing to the payload module. This passive cooling system brings the temperature of the telescope down to around 50K. The temperature of the detectors is further decreased to levels as low as 0.1K by a three-stage active refrigeration chain. The resulting difference in temperature between the warm and cold ends of the satellite is an astounding 300 degrees.

Microwaves are a specific kind of electromagnetic radiation. Electromagnetic radiation, which is simply light, can be thought of as a wave which carries a certain energy. Light of different energy needs different detectors to be 'seen'. Microwaves, for instance, cannot be detected by our eyes, which are instead perfectly tuned to see a more energetic kind of light called, for obvious reasons, visible light. The energy of light is often described in terms of wavelength (a length scale) or frequency (a time scale). The typical wavelength of microwaves is in the order of millimetres.



Planck will chart the best ever all-sky maps in its range of wavelengths. ESA (image by C.Carreau)

The coldest detectors

A key requirement is that Planck's detectors must be cooled to temperatures close to the coldest temperature reachable in the Universe: absolute zero, which is −273.15°C, or, expressed in the scale used by scientists, zero kelvin (0K).

At the time of its release, only about 380 000 years after the Big Bang, what we detect as the CMB today had a temperature of some 3000K; but now, with the expansion and cooling of the Universe, the temperature of this radiation appears to be only 2.7K (about −270°C). The detectors on board Planck have to be very cold so that their own heat does not swamp the signal from the sky. All of them will be cooled down to temperatures around or even below −253°C, and some of them will reach the amazingly low temperature of just one tenth of a degree above absolute zero. These detectors could well be the coldest points in space.

Sharp vision

With its unprecedented angular resolution, Planck will provide the most accurate measurements of the CMB yet.

The angular resolution is a measure of Planck's sharpness of vision, i.e. the smallest separation between regions in the sky that the detectors are able to distinguish; the smaller the separation, the sharper (better) will be the information gathered. Planck's sharpness of vision is such that it can distinguish objects in the sky with a much higher resolution than any other space-based mission that has studied the CMB.

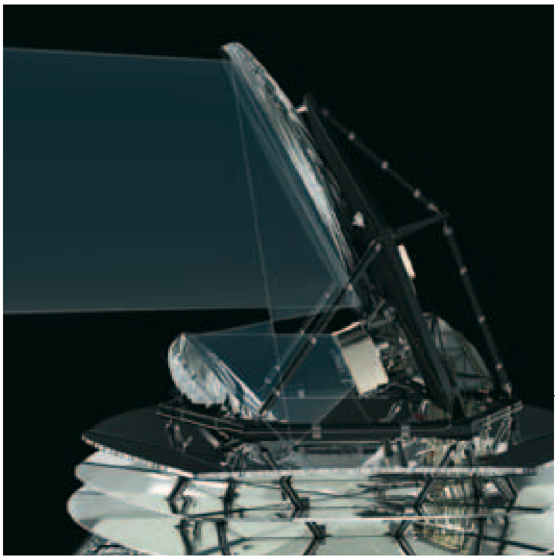
Planck's detectors have the ability to detect signals 10 times fainter than its most recent predecessor, NASA's WMAP, and its wavelength coverage allows it to examine wavelengths 10 times smaller. In addition, the telescope's angular resolution is three times better. The resulting effect is that Planck will be able to extract 15 times more information from the CMB than WMAP.

With its sharp vision and high sensitivity, Planck will extract all the information held in the CMB temperature variations.

Broad wavelength coverage

The Planck detectors are specifically designed to detect microwaves at nine wavelength bands from the radio to the far-infrared, in the range of a third of a millimetre to one centimetre. This includes wavelengths that have not been observed before with the precision and sharpness offered by Planck. The wide coverage is required in order to face a key challenge of the mission: to differentiate between useful scientific data and the many other undesired signals that introduce spurious noise. The problem is that many other objects, such as our own galaxy, emit radiation at the same wavelengths as the CMB itself. These confusing signals have to be monitored and removed from the measurements; Planck will use several of its wavelength channels to measure signals other than the CMB, thus obtaining the cleanest signal of the CMB ever.

In addition, as it is monitoring signals other than the CMB, Planck is gathering data on celestial objects including star fields, nebulae and galaxies with unprecedented accuracy in the microwave, providing scientists with the best astrophysical observatory ever in this wavelength range.



The Planck telescope. ESA (AOES Medialab)

Planck's eyes

The Planck telescope

The Planck telescope collects radiation from the CMB and delivers it to the detectors. The primary mirror, 1.9x1.5 m in size, is very large for a space mission, and weighs only about 28 kg. The mirror is robust enough to withstand the stresses of launch as well as the temperature difference between launch, when it is at ambient temperature (about 300K), and operations (about 40K). The mirror is made of carbon fiber reinforced plastic coated with a thin reflective layer of aluminium (reflectivity >99.5%). The telescope is surrounded by a large baffle that minimises stray light interference from the Earth, Sun and Moon, and cools it by radiating heat into space.

The telescope mirrors were provided thanks to a collaboration between ESA and a Danish consortium of scientific institutes led by the Danish National Space Centre.

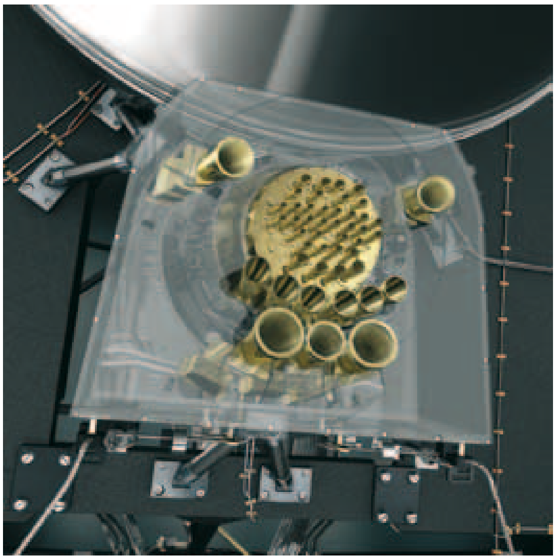
Planck instruments

Planck carries two complementary scientific instruments: the High Frequency Instrument (HFI), and the Low Frequency Instrument (LFI). They will provide accurate estimates of the spatial variations of the temperature of the CMB, key to understanding the origin of the Universe and the evolution of galaxies.

The High Frequency Instrument (HFI) is designed for high-sensitivity measurements of the diffuse radiation permeating the sky in all directions at six wavelength bands in the range 3.6 mm to 0.3 mm (frequency range 84 GHz to 1 THz). The instrument consists of an array of 52 bolometric detectors placed in the focal plane of the telescope and cooled to a temperature of 0.1K. Bolometric detectors are devices capable of detecting and measuring small amounts of thermal radiation, and they work by converting radiation to heat.

HFI was built by a Consortium of more than 20 institutes, led by the Institut d'Astrophysique Spatiale in Orsay (France).

Planck focal plane. HFI is visible as circular forest of horns at the centre, surrounded by the LFI ring of horns. ESA (AOES Medialab)

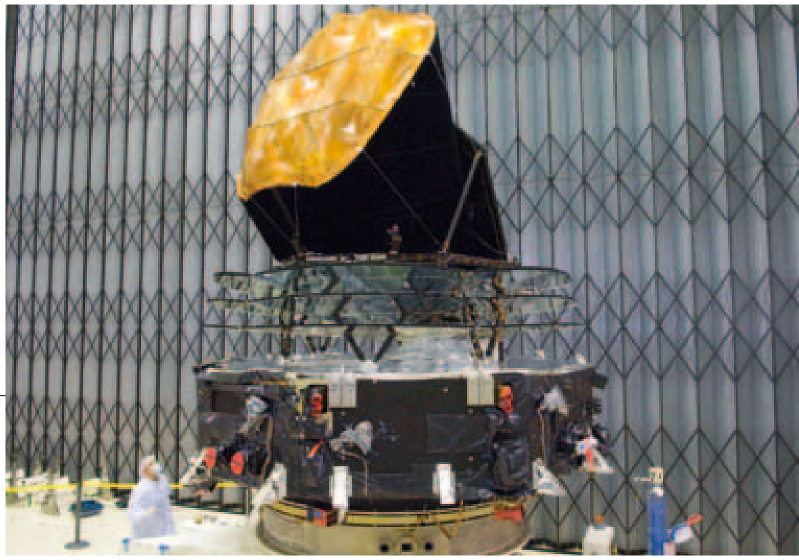


The Low Frequency Instrument (LFI) is designed for high-sensitivity measurements of the microwave sky at three wavelength bands in the range 11.1 mm to 3.9 mm (frequency range 27 GHz to 77 GHz). The instrument consists of an array of 22 tuned radio receivers located in the focal plane of the telescope that will operate at −253°C. These radio receivers gather microwaves from the sky and convert them into an estimate of the intensity of radiation at each frequency.

LFI was built by a consortium of more than 20 institutes, led by the Istituto di Astrofisica Spaziale e Fisica Cosmica in Bologna (Italy).

Several funding agencies contributed to the LFI and HFI instruments and respective data centres; the major ones are: CNES (France), ASI (Italy), NASA (USA), STFC (United Kingdom), DLR (Germany), NSC (Norway), Tekes (Finland), Ministry of Education and Science (Spain), plus ESA.

Who built Planck?



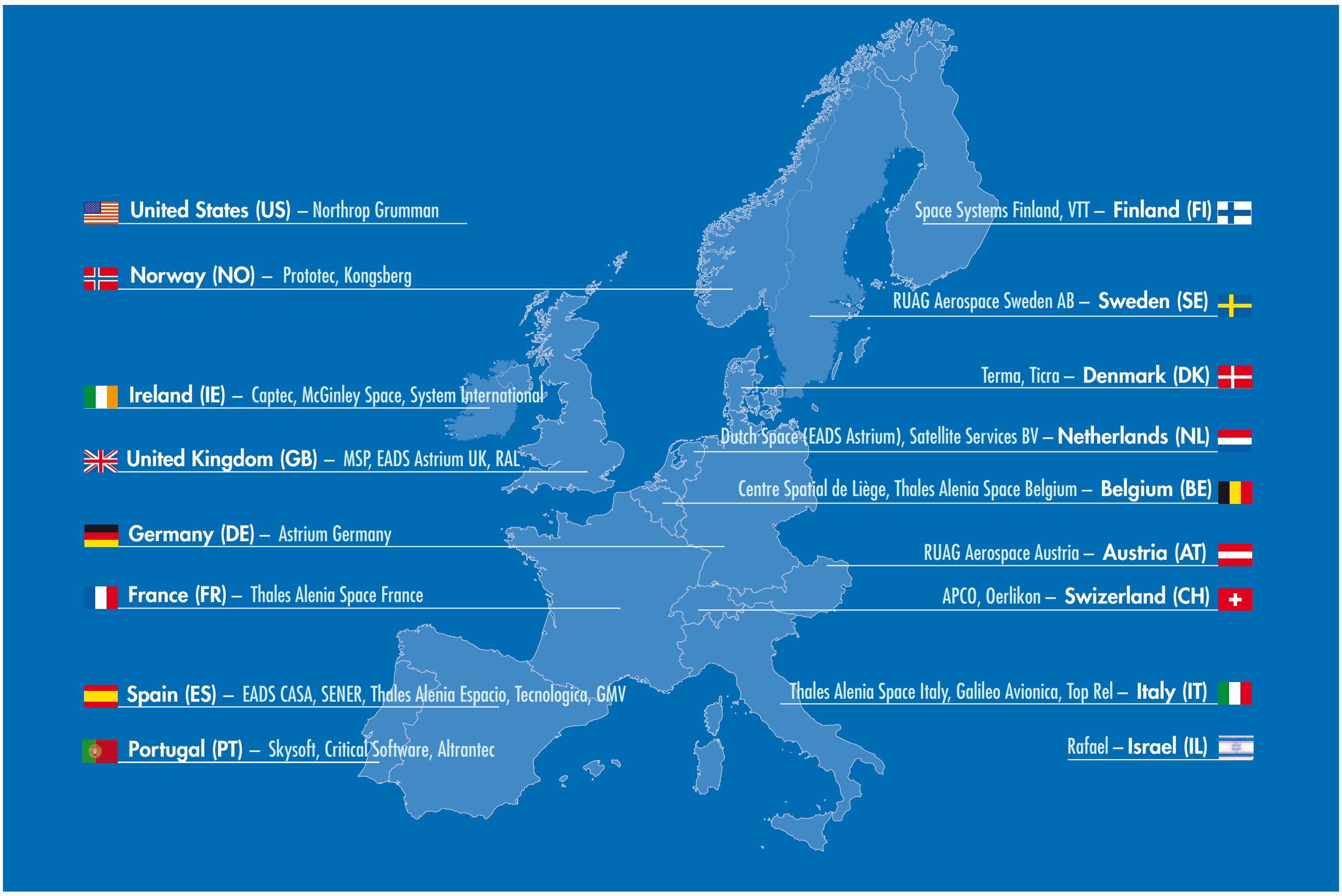
Planck being prepared for tests at the European Space Research and Technology Centre (ESTEC), The Netherlands.

Planck's state-of-the-art design presented several technological challenges, in particular its sophisticated cooling system that keeps the spacecraft detectors at extremely cold temperatures – close to absolute zero.

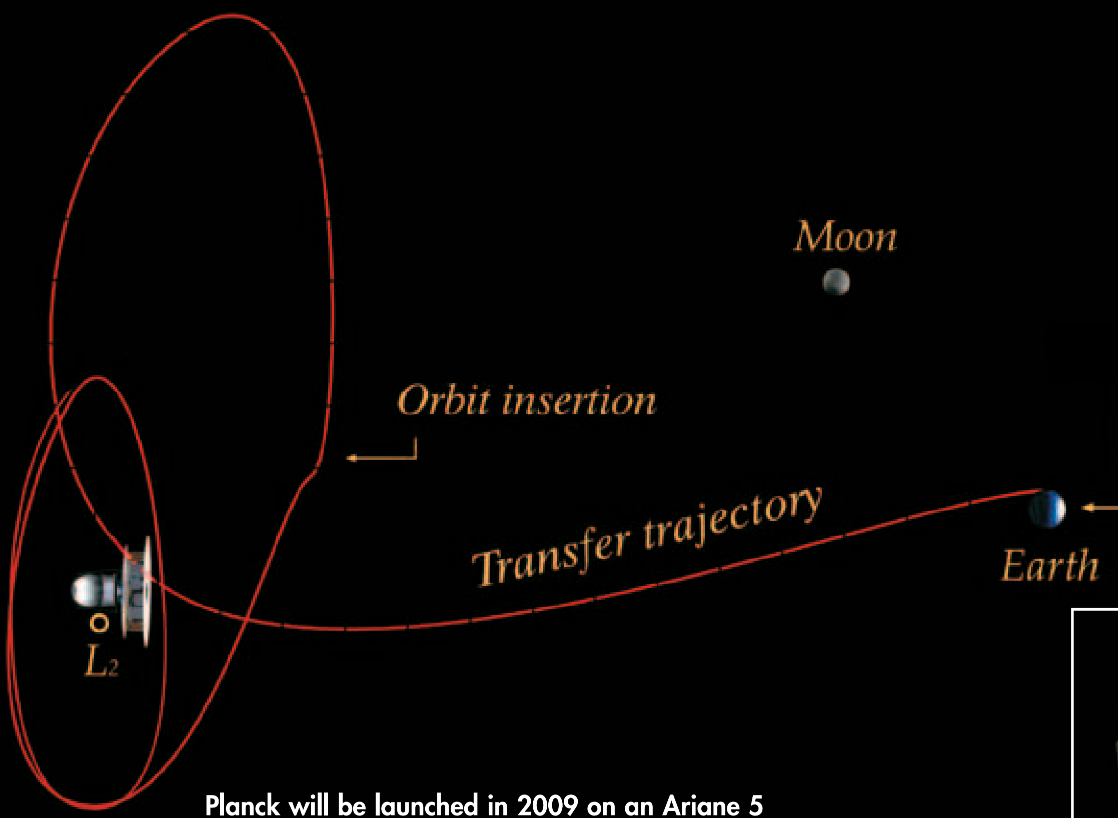
ESA has designed and built Planck under a common engineering programme with Herschel, ESA's infrared space observatory that will study the formation of galaxies and stars. The two satellites will share more than just a launcher: they have undergone a joint development process aimed at optimising resources, by using the same industrial teams and shared design of spacecraft components wherever possible.

ESA's prime contractor for Planck is Thales Alenia Space (Cannes, France), leading a consortium of industrial partners with Thales Alenia Space (Turin, Italy) responsible for the service module. There is also a host of subcontractors spread throughout Europe, with a few more in the USA. ESA and the Danish National Space Centre (Copenhagen, Denmark, funded by the Danish Natural Science Research Council) provided Planck's telescope mirrors, manufactured by Astrium (Friedrichshafen, Germany).

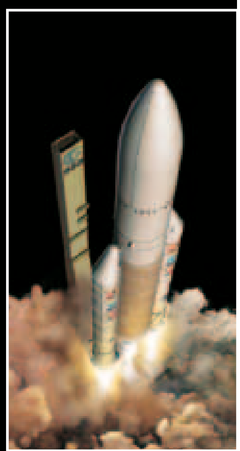
ESA's industrial partners.



1.5 million km from Earth



ESA (Guarniero)

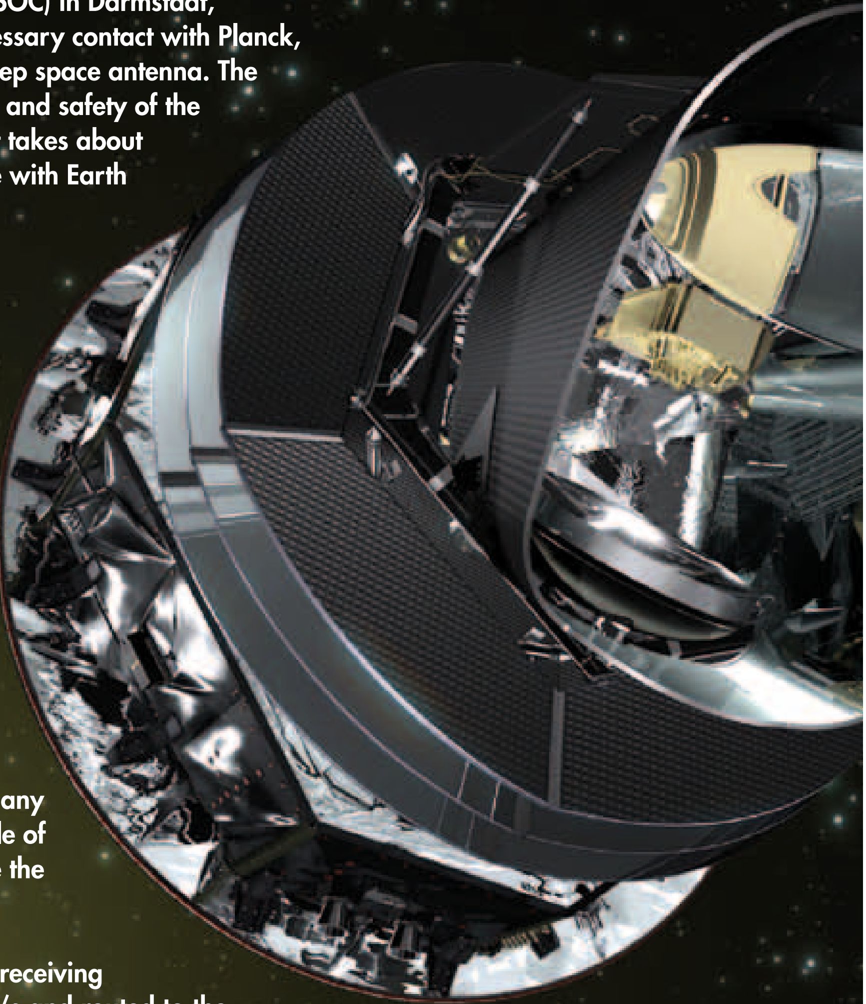


Planck will be launched in 2009 on an Ariane 5 along with ESA's Herschel space observatory. After separating from the upper stage, the two satellites will head towards their respective orbits. They will be operated independently.

About 60 days after launch Planck will reach its final operational orbit, following a few manoeuvres. Its operational orbit will be a Lissajous orbit with an amplitude of about 400 000 km around the second Lagrangian point of the Sun–Earth system, or L2. This is a virtual point in space located about 1.5 million km from Earth – four times the distance to the Moon. From this position, Planck will be able to avoid unwanted emission from the Earth, Moon and Sun, which would otherwise confuse the signal from the CMB.

Operating Planck

Planck will be operated by the mission operations team at the Mission Operations Centre (MOC) which is located at ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany. The team maintains all necessary contact with Planck, using ESA's New Norcia (Australia) deep space antenna. The team is also responsible for the health and safety of the spacecraft. From its orbit around L2, it takes about 10 seconds for Planck to communicate with Earth (two-way).



ESA (AOES Medialab)

The spacecraft carries out science observations continuously, and the data collected are recorded on the on-board computer. Planck communicates with Earth for about three hours each day, during which time the team downloads the acquired data and uploads new commands for execution on the following day.

The Planck science planning team, located at ESA's European Space Astronomy Centre (ESAC) in Spain, collects inputs from the instrument teams. These inputs are used to make any necessary modifications to the schedule of observations which is used to produce the mission operations timeline.

Scientific data are downloaded to the receiving station on Earth at a rate of 1.5 Mbits/s and routed to the MOC at ESOC. From there, the data are sent to the instrument data processing centres, where they are processed and analysed. The relevant spacecraft and science data are also sent to the instrument operations centres where they are used to monitor and optimise the instruments' performances.

The data processing centre and the operations centre for the HFI are located at the Institut d'Astrophysique de Paris, France, and Institut d'Astrophysique Spatiale d'Orsay, France, respectively, whereas those for the LFI are located at the Osservatorio Astronomico di Trieste, Italy.

The nominal mission ends in 2010. In 2012, the processed scientific data will be archived at ESAC and made available to the worldwide astronomy community.

Planck in a nutshell

Concept:
Planck is an ESA mission that has been designed to answer key questions for humankind: How did the Universe come to be? How will it evolve? The mission objective is to study the Universe's first light, the Cosmic Microwave Background (CMB), with unprecedented accuracy. It will measure the fluctuations of the CMB with an accuracy set by fundamental astrophysical limits.

Highlights:
- Planck will study the CMB more sharply and sensitively than ever before.
- Thanks to the accuracy of this first image, it will extract far more information about the early phases of the Universe than any previous space mission.
- It will study all of the Universe's constituents with unprecedented accuracy. For example, it will determine the total amount of normal and dark matter in the Universe, and it will investigate the nature of dark energy.
- It will study the evolution of the Universe in cosmic timescales, determining for example, when the first stars formed.
- As an additional benefit, it will be the most sophisticated astrophysical observatory to operate in the microwave: as it works to obtain a clean CMB signal, Planck will gather data on other celestial objects with unprecedented accuracy.

Launch:
Planck will be launched in 2009 along with ESA's Herschel space observatory, on board an Ariane 5 from Europe's Spaceport in Kourou, French Guiana. The satellites will operate independently from different orbits.

Orbit:
Both Planck and Herschel will orbit the second Lagrangian point (L2), a virtual point in the Sun–Earth system, located 1.5 million km from Earth. Planck's orbit will be a Lissajous orbit at a distance of about 400 000 km from L2.

Telescope and instruments:
Planck will carry a telescope with an effective aperture of 1.5 m. It will focus radiation from the sky onto two arrays of sensitive detectors, that of the Low Frequency Instrument and that of the High Frequency Instrument. Together they will measure the temperature of the CMB over the sky, searching for regions very slightly warmer or colder than the average.

Wavelength coverage:
Nine bands, from one centimetre to one third of a millimetre, corresponding to a range of wavelengths from microwaves to the very-far-infrared.

Launch mass:
About 1.9 tonnes.

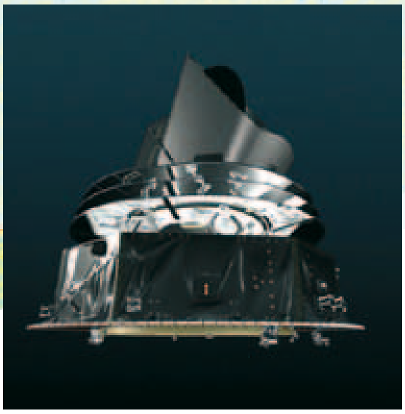
Dimensions:
Approximately 4.2 m high and 4.2 m wide.

Operations:
Planck will slowly rotate and sweep a large swath of the sky each minute. In about 15 months it will have covered the sky fully, twice over. It will operate continuously and mostly autonomously, and will send the data acquired each day to a ground station over a three-hour period.

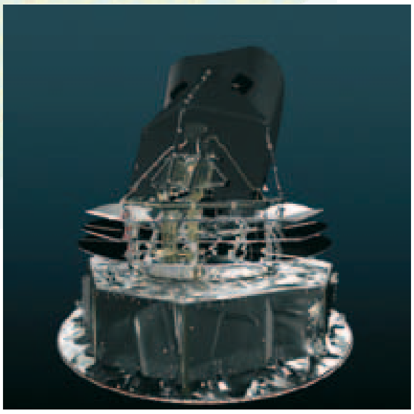
Primary ground station:
ESA's deep space antenna in New Norcia, Australia.

Operational lifetime:
15 months of routine science operations. A 1-year extension is possible.

The Planck payload is kept in the shade and has a temperature of about –220°C.



The bottom of the satellite is warm and contains all the electronics and other subsystems.



The Planck satellite: an intricate maze of pipes, wires and waveguides connects the warm and cold parts of the satellite.

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